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Magnetic Gearing of Permanent Magnet Brushless Motors

This invention relates to the magnetic gearing of permanent magnet brushless motors.

Permanent magnet brushless motors are known which are capable of providing variable speed outputs. The motor characteristics are linear, generating high torque at low speeds and high speed at low torque levels.

In certain applications, the range of speed and torque characteristics of a particular motor may not be sufficient to cover the desired range, even though the output power of the motor may be sufficient. In such circumstances two options are available. Firstly, a more powerful motor could be used to cover the entire range or secondly, mechanical gears could be provided for the motor. Both of these methods add cost and weight to the system.

Canadian Patent Application No. 2341095 discloses an alternative to the above-mentioned methods which uses a technique in which the speed and torque can be varied inside the motor and the only additional item required is a switching circuit. A prerequisite of this technique is that the stator coils of the motor must be segmented into at least two or more sections, which are evenly or perhaps unevenly distributed throughout the stator slots. The switching circuit can then be used to change the number of coil segments which are connected to the supply. Such an arrangement utilises the control of the induced back electromotive force (back emf) to control the speed by selectively altering the number of conductors which are connected to the supply. This in effect also alters the torque with changing speed of the motor.

In the main embodiment of Canadian Patent Application No. 2341095, each of the motor windings comprises a plurality of series-connected sections provided by tappings in the winding, which can be selectively connected across the supply. With just one of the coil segments connected across the supply, the motor will produce a high speed but a low torque. However,

with a higher proportion of coils connected in series across the supply, the motor will produce a lower speed at the same torque. In this manner, the speed but not the torque of the motor can be varied by selectively connecting the windings in  
5 series.

In an alternative embodiment, each of the motor windings comprises a plurality of parallel-connected sections, which sections can be selectively connected in parallel across the supply. With just one of the coil segments connected across  
10 the supply, the motor will produce a high speed but a low torque as previously described. However, with a higher proportion of coils connected in parallel across the supply, the motor will produce high torque at the same speed. In this manner, the torque but not the speed of the motor can be varied  
15 by selectively connecting the windings in parallel.

A disadvantage of either arrangement is that sections are redundant when running the motor during some configurations and thus copper ( $I^2R$ ) losses will be higher because the cross-sectional area of copper utilised decreases as the number  
20 of active sections decreases. Also, the presence of redundant sections means that the net resistance of the coils is not optimised in all configurations and hence the supply current or voltage has to be controlled to avoid damaging the connected coils. Since speed and torque are functions of the current, any  
25 limitation of the current affects the performance of the motor.

In most situations, the supply current to the motor is limited (for example in domestic mains to 13 amps), and thus the attainable speed and torque will not be optimised when some coils are out of circuit.

30 We have now devised a permanent magnet brushless motor which alleviates the above-mentioned problem.

In accordance with this invention, there is provided a permanent magnet brushless motor comprising a winding divided into a plurality of sections and switch means for selectively  
35 connecting the sections of the winding in one of a plurality

of different configurations, wherein each section is connected in series and/or parallel with all other sections of the winding.

The switch means can then be used to change magnetic  
5 gears, by changing the configuration of the coil segments in series, parallel or a combination of both, which are connected to the supply. We call such an arrangement magnetic gearing because it utilises the control of the induced back  
electromagnetic force (back emf) to control the speed by  
10 selectively altering the winding configuration which are connected to the supply. This alters the torque with changing speed of the motor.

In contrast to known methods of varying the speed or torque by coil manipulation, the present invention is  
15 distinguished in that all of the winding segments contribute towards the motor operation no matter which section configuration is being employed. In this manner, all of the available copper is utilised at all times, thereby keeping the copper loss of the motor to a minimum.

20 The advantage of utilising all of the winding sections is the reduction of the motor's copper loss. Normally the stator slots are packed with as much copper wire as possible, either by maximising the number of turns, or by maximising the wire diameter (if the number of turns have been predetermined  
25 for the design). In this manner the cross-section area of copper is maximised for the slot, so that the resistance of the coils is kept to a minimum. Hence the copper loss for the motor will always be kept to a minimum.

In a first configuration, the switch means is  
30 preferably arranged to connect all of the winding sections in parallel. In this configuration at a given current  $I$ , the motor is able to reach high speeds at relatively low torque levels.

In a second configuration, the switch means is preferably arranged to connect all of the winding sections in  
35 series. In this configuration at the same current  $I$ , the motor

is only able to deliver high levels of torque at relatively low speeds.

In a third configuration, the switch means is preferably arranged to connect some of the winding sections in parallel, with at least one other section being connected in series with the parallel-connected sections. In this configuration at the same current, the motor is able to reach speeds between that of the first and second configurations and deliver a torque between the first and second configurations.

In order to further vary the speed v torque characteristic of the motor, the voltage applied to the winding may be pulse-width modulated, for example using said switch means.

The speed v torque characteristic of the motor may also be varied by rapidly switching the winding sections between different configurations to obtain a characteristic intermediate that of the configurations between which the windings are switched.

Preferably the switch means is able to vary the configuration of the winding connections whilst the motor is running, in accordance with predetermined operating parameters.

Preferably, the switch means is able to vary the configuration of the winding connections whilst the motor is running, in accordance with the output of means for sensing an operating parameter of the motor such as the current, voltage, speed or torque, or in accordance with the output of means for sensing an operating parameter of the article being driven by the motor such as velocity. In the case of a multi-phase motor having a plurality of windings, the switch means may vary the configuration of the winding connections of a conducting phase whilst the motor is running, in accordance with the back emf measured across the winding of non-conducting phase or a section thereof.

Alternatively, the switch means is able to vary the configuration of the winding connections in accordance with

time or an operating cycle or program.

Alternatively, means may be provided for manually changing the configuration of the winding connections.

Preferably all of the sections of the winding are wound  
5 in parallel during assembly, with the current preferably flowing through each section in the same direction.

One of the sections of the winding may comprise a different number of turns from another section. Also, one of the sections of the winding may comprise a conductor having a  
10 different cross-sectional area than the conductor of another section.

An embodiment of this invention will now be described by way of an example only and with reference to the accompanying drawings, in which:

15 Figure 1 is a schematic diagram of one phase of a 3-phase permanent magnet brushless motor in accordance with the present invention;

Figures 2 to 6 are schematic diagrams showing various connections of sections of the motor of Figure 1;

20 Figure 7 is a table showing the switch states of the motor of Figure 1 with reference to the connections of Figures 2 to 6;

Figure 8 is a graph of speed  $v$  torque for the connections of Figures 2 to 6; and

25 Figure 9 is graph of speed  $v$  torque to illustrate how the ideal motor characteristics for a washing machine can be achieved using the motor of Figure 1.

Referring to Figure 1 of the drawings, there is shown a 3-phase permanent magnet brushless DC motor comprising three  
30 star-connected phases R,Y,B 18 slots, 12 poles and a slot pitch of 1. The stator outer diameter, inner diameter and length are 110mm, 55mm and 75mm, respectively. The air gap is 0.5mm, the magnet width and thickness are 10mm and 4 mm, respectively. Each phase comprises a winding having, for example, five  
35 conductors or so-called sections 1-5 of 0.63mm enamelled copper

which are co-wound in parallel through the relevant stator slots of the motor. The supply voltage to the motor is 180 volts DC.

The first end of the first section 1 of one phase R is  
5 connected to the first ends of the first sections of the other two phases Y, B. The first end of the first section of the phase R is also connected to the first end of the second section 2 of that phase R via a switch S1. Likewise, the first ends of the other sections 3,4,5 are connected to adjacent  
10 sections via respective switches S2, S3, S4.

Similarly, the second end of the first section 1 of the phase R is connected to the second end of the second section 2 of that phase R via a switch S9. Likewise, the second ends of the other sections 3,4,5 are connected to adjacent sections  
15 via respective switches S10, S11, S12. The second end of the fifth section 5 is also connected to the supply.

The second end of the first section 1 of the phase R is connected to the first end of the second section 2 of that phase R via a switch S5. Likewise, the second ends of the other  
20 sections 2,3,4 are connected to the first ends of adjacent sections via respective switches S6, S7, S8.

Referring to Figures 2, 7 and 8 of the drawings, when the motor is initially started, only the switches S5 to S8 are energised such that the sections 1-5 are connected in series.  
25 In this manner the supply current flows through each series-connected section 1-5 in the same direction with respect to each section's polar orientation (as indicated by the arrows in Figure 1): it is imperative that this is always the case. Had one of the sections (e.g. section 4) been oriented in the  
30 opposite direction, the flux produced by section 4 would oppose the flux produced by sections 1, 2, 3 and 5.

The torque of the motor is directly proportional to the current and, as long as the starting torque is high enough to overcome the load attached to the motor, the rotor begins to  
35 turn. This is accompanied by the generation of a back emf in

the coils, which begins to cancel out the supply voltage, so that the current available for the phase coils begins to reduce, as does the torque produced by the motor.

The back emf, is directly proportional to the number of turns in the phase coils, the magnetic flux produced by the permanent magnets, the number of permanent magnet pole pairs and the angular speed of the rotor. Other factors, such as the interconnection between the coils and the phases and the number of phases also affects the back emf generated.

10 The consequence of this behaviour is that, the motor will continue to accelerate until the torque produced by it, equals the load. From this point on, the motor will continue to rotate at a constant speed. If at any instance the load is altered, the motor will automatically adjust its torque (and  
15 consequently, its speed) in order to balance the load.

The maximum speed that can be attained by a motor, occurs when there is no load attached to the motor. Ideally, this occurs when the back emf generated in the phase coils is equal to the supply voltage, at which instance there is no  
20 current flowing through the coils to produce any torque; this situation is referred to as the no load speed.

In reality, the back emf will always remain marginally lower than the supply voltage (even at no load speed). This is because a small portion of power supply is used up in  
25 overcoming frictional forces due to windage and the bearings, as well as iron losses of the motor.

It is evident from the graph of Figure 8 that the motor is limited to performance criteria within the speed v torque line for Figure 2. The graph indicates that the motor can  
30 manage a maximum speed of 584 rpm and a maximum torque of 28.1 Nm. As a further example, it can also provide torque of 8 Nm up to a maximum speed of approximately 400 rpm, or conversely, the motor running at 400 rpm, can provide up to a maximum torque of approximately 8 Nm.

35 If the desired motor performance falls beyond the 10

amp line, for instance 14 Nm-at 600 rpm, the motor parameters need to be altered in order to cater for the additional power requirements.

Referring to Figures 3, 7 and 8 of the drawings, the motor's performance can be changed by altering the configuration in which all of the motor's windings are connected. By energising the switches in accordance with Figure 7, sections 1 and 2 can be connected in parallel and this parallel set is then connected in series with section 3, 4 and 5 (which are connected in series with one another).

It is evident from the graph of Figure 8 that the motor is now limited to performance criteria within the speed v torque line for Figure 3. The graph indicates the motor will now generate a no load speed of 725 rpm and a stall torque of 34.6 Nm.

Referring to Figures 4, 7 and 8 of the drawings, the motor's performance can be changed again by energising the switches in accordance with Figure 7, so that sections 1, 2 and 3 are connected in parallel and this parallel set is then connected in series with sections 4 and 5 (which are connected in series with one another).

It is evident from the graph of Figure 8 that the motor is now limited to performance criteria within the speed v torque line for Figure 4. The graph indicates the motor will now generate a no load speed of 966 rpm and a stall torque of 46.1 Nm.

Referring to Figures 5, 7 and 8 of the drawings, the motor's performance can be changed again by energising the switches in accordance with Figure 7, so that sections 1, 2, 3 and 4 are connected in parallel and this parallel set is then connected in series with section 5.

It is evident from the graph of Figure 8 that the motor is now limited to performance criteria within the speed v torque line for Figure 5. The graph indicates the motor will now generate a no load speed of 1449 rpm and a stall torque of



69.0 Nm.

Referring to Figures 6, 7 and 8 of the drawings, the motor's performance can finally be changed by energising the switches in accordance with Figure 7, so that sections 1, 2, 3, 4 and 5 are connected in parallel.

It is evident from the graph of Figure 8 that the motor is now limited to performance within the speed v torque line for Figure 6. The graph indicates the motor will now generate a no load speed of 2898 rpm and a stall torque of 136.7 Nm.

At first sight, one may consider that the best option would be to implement the configuration of Figure 6 (i.e. all sections in parallel), since this choice yields the greatest range in terms of both speed and torque. However, although the voltage supplied to all of the configurations is the same (180 volts DC), the current varies from one configuration to the next. In practical applications there will always be a current limit, for example most household appliances are limited to 13 amps. Referring to Figure 8, if a notional 10 amp limit is applied to each configuration, it will be seen that the maximum torque achievable by the configuration of Figures 2 to 6 are 29.7, 23.7, 17.8, 11.9 and 5.9 Nm respectively. Thus, by operating the switches to change between the various configurations, whilst keeping the motor within the confines of the 10 amp limit, a performance can be achieved as shown in the shaded area of the graph. Accordingly, it will be appreciated that a gearing system for the motor can be provided by operating the switches, thereby allowing the motor to generate higher torque (at low speed) and higher speed (with low torque) than would be possible with any single configuration (with limited current supply). Thus, when the motor is initially energised, all sections can be connected in series as shown in Figure 2, such that a high starting torque is achieved well within the confines of the 10 amp limit.

The switches S1 to S12 can be relays or semiconductor devices. In the case of semiconductor devices, a plurality of

devices could be included in a single package. Individual switches for example S1, S5 and S9 can be configured into a single mechanical or electronic switch. In this case when 1 and 9 are ON, then 5 is OFF. When 5 is ON, then 1 and 9 are OFF.  
5 This way only 4 switches will be required per phase instead of 12 switches.

Referring to Figure 9 of the drawings, there is shown a graph of the required speed  $v$  torque curve 20 for a domestic washing machine superimposed onto the graph of Figure 8. At  
10 present the required speed and torque are normally achieved by using induction motors running at high speeds with appropriate mechanical gearing and drive belts, or by using a large DC direct drive motor. However, it can be seen that the required range of speed and torque can easily be achieved within the  
15 current confines using a reasonably sized direct drive brushless DC motor in accordance with this invention.

It will be seen that the configurations of Figures 3 and 4 are not necessary to provide the required speed  $v$  torque curve for a domestic washing machine and thus some cost savings  
20 can be achieved by omitting some of the switches.

It should be noted that the multi-segmented coils within a single phase need not be wound using the same wire diameter or the same number of turns, however, all the phases must be wound in an identical manner. For instance, section 1  
25 of every phase must be wound with the same wire and have the same number of turns. Coil section 2 can have a different number of turns and it can be wound using a different wire diameter to that of section 1, but coil segment 2 of every phase must be identical and the same applies to all other  
30 segments.

It will be appreciated that whilst the embodiment hereinbefore described utilises 3-phases, the invention applies to a motor having any number of phases. Furthermore, the invention also applies to permanent magnet brushless  
35 synchronous motors, which have similar speed torque

characteristics.

The configurations discussed in Figures 2 to Figures 6 are not the only possible combinations. For example, another possible combination is coil sections 1 and 2 connected in parallel and coil sections 3 and 4 connected in parallel, the two parallel sets being connected in series with one another and with the remaining section 5. This configuration will produce the same motor characteristics as the arrangement shown in Figure 4.

Yet another configuration can be obtained by connecting sections 1, 2 and 3 in parallel and sections 4 and 5 in parallel and then connecting the parallel sets in series with one another. This will yield motor characteristics that are the same as the one produced by the configuration shown in Figure 5.

The number of speed-torque characteristics that can be obtained is dependent on the number of winding sections provided (per phase), which is limited to some finite number. The motor operates at its most efficient level when it is running as close as possible to its no load speed. For this reason, it is undesirable to allow the motor to compensate for an increase in load, by automatically reducing its speed (on the speed-torque characteristics line). It would be far better to meet the demands of the increase in load through magnetic gearing, so that the new torque level is achieved whilst the motor continues to run close to its no load speed. However, in order to meet all possible torque levels (within the given range of the motor) the motor would require an infinite number of magnetic gears and therefore, an infinite number of winding sections and switches.

In an alternative embodiment, it is possible to achieve any speed torque curve in between those obtained by altering the configuration of the windings by interchanging between the two configurations very rapidly, so that the motor is not operating at the characteristics of either configuration, but

somewhere in between. The rapid switching between the two configurations can be achieved by feeding a pulse width modulated (PWM) signal to the switches (S1 to S12) and the duty cycle of the PWM is altered to achieve the desired intermediate  
5 speed and torque.

For example, consider a first configuration with all winding sections connected in parallel; this gear provides the highest speed the motor can achieve and therefore, it is the highest gear. The next gear down from this, is achieved by  
10 connecting one of the winding sections in series with the remaining parallel sections; this provides the next highest speed.

If the PWM has a duty cycle of 100%, the gear will change from the highest to the next lower gear and remain  
15 there. Conversely, if a duty cycle of 0% (i.e. no signal) is chosen, the motor will remain in the highest gear. Choosing a duty cycle between 0 and 100% will yield a gear and consequently, a motor speed and torque between the highest two gears; i.e. an intermediate gear.

20 If desired, the gearing can be switched directly between the highest gear (all sections in parallel) and the lowest gear (all sections in series). The duty cycle of the PWM can then be used to select a speed/torque characteristics anywhere in between the two extremes of the motor performance.  
25 However, the resolution and consequently, the accuracy with which a desired speed can be achieved decreases as the full range of the gearing scale increases. This, to some extent can be compensated by increase in PWM frequency.